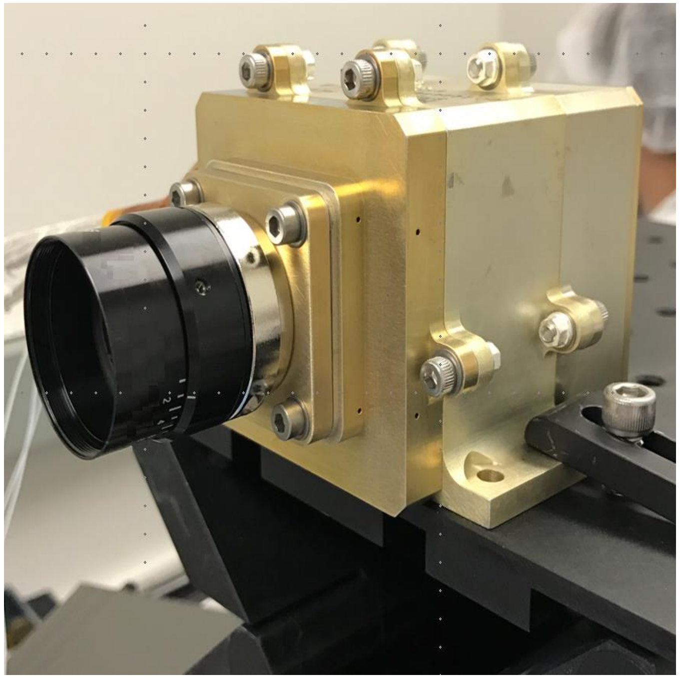

Context Cameras for the Orbiting Carbon Observatory 3 (OCO-3) Instrument

Colin McKinney, Timothy Goodsall, Michael Hoenk, Jacob Shelton, Christophe Basset, Keith Rumney, Douglas Moore, Muthu Jenganathan
Jet Propulsion Laboratory, California Institute of Technology
March 4, 2018
IEEE Aerospace Conference, Big Sky, MT

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California Institute of Technology

Agenda

- Background
  - OCO-3 Mission Summary
- Context Camera suite
  - Camera developments at JPL
  - Design
  - Implementation
  - Functional testing and calibration
  - Environmental Testing
- Future applications

OCO-3 MISSION SUMMARY

OCO-3 Project Overview

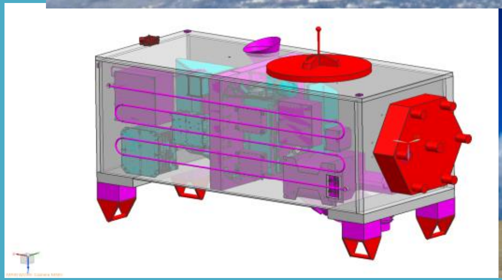
OCO-3 is a NASA-directed Climate Mission on the International Space Station

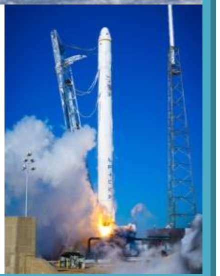
Primary Science Objectives

- Collect the space-based measurements needed to quantify variations in the column averaged atmospheric carbon dioxide (CO_2) dry air mole fraction, X_{CO2}, with the precision, resolution, and coverage needed to improve our understanding of surface CO_2 sources and sinks (fluxes) on regional scales (≥1000 km).
  - Measurement precision and accuracy requirements same as OCO-2
  - Operation on ISS allows latitudinal coverage from 51 deg S to 51 deg N

Salient Features:

- Category 3 mission per NPR 7120.5E
- Risk classification C per NPR 8705.4
- High-resolution, three-channel grating spectrometer (JPL)
- Partnership between SMD and HEOMD
- Deployed on the International Space Station
- Payload Delivery Date: TBD
- Operational life: 3 years after 90 days In orbit Checkout
- Project Scientist: Dr. Annmarie Eldering
- Project Manager: Dr. Ralph Basilio





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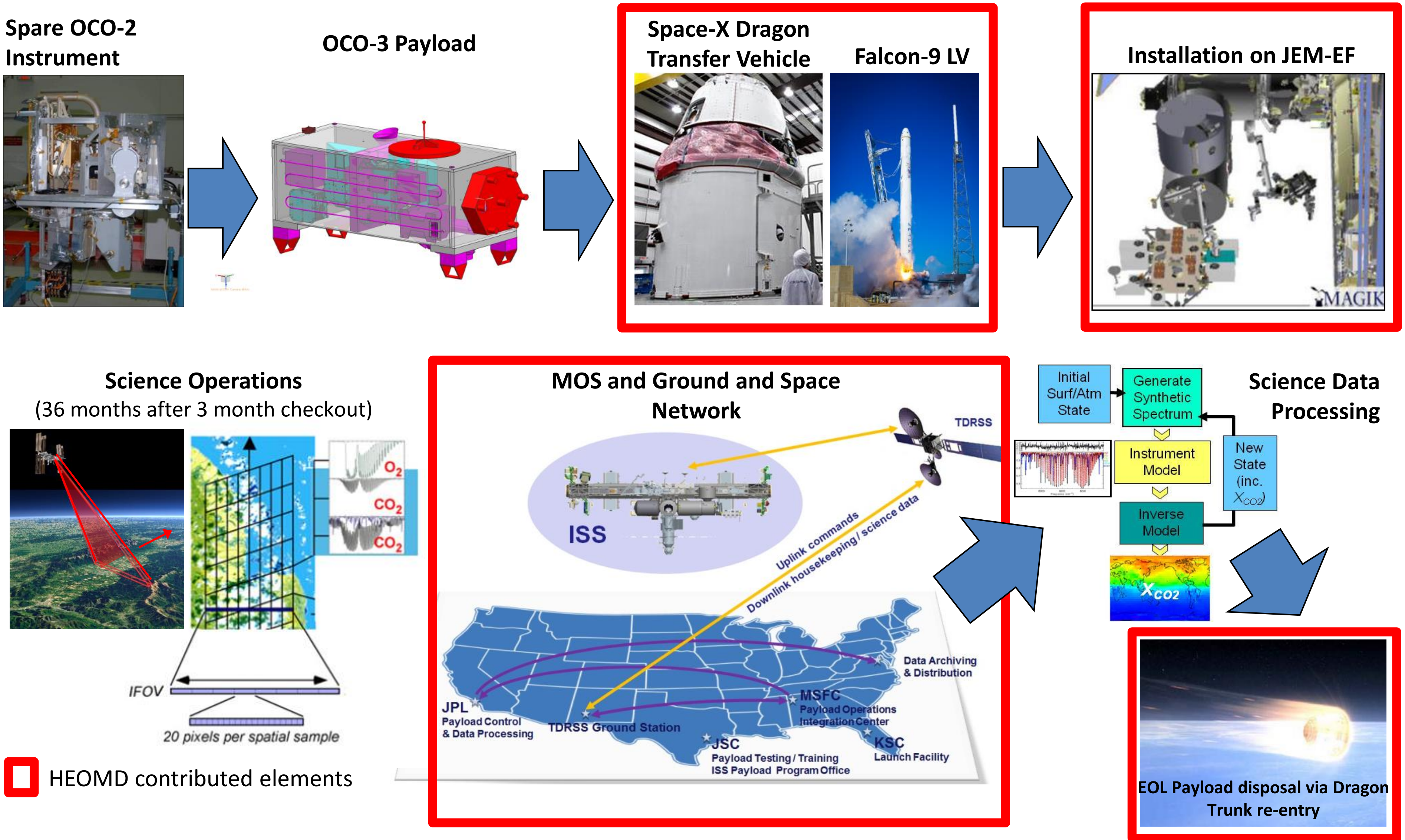
OCO-3 Mission Concept and Architecture



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Context Cameras for Calibration

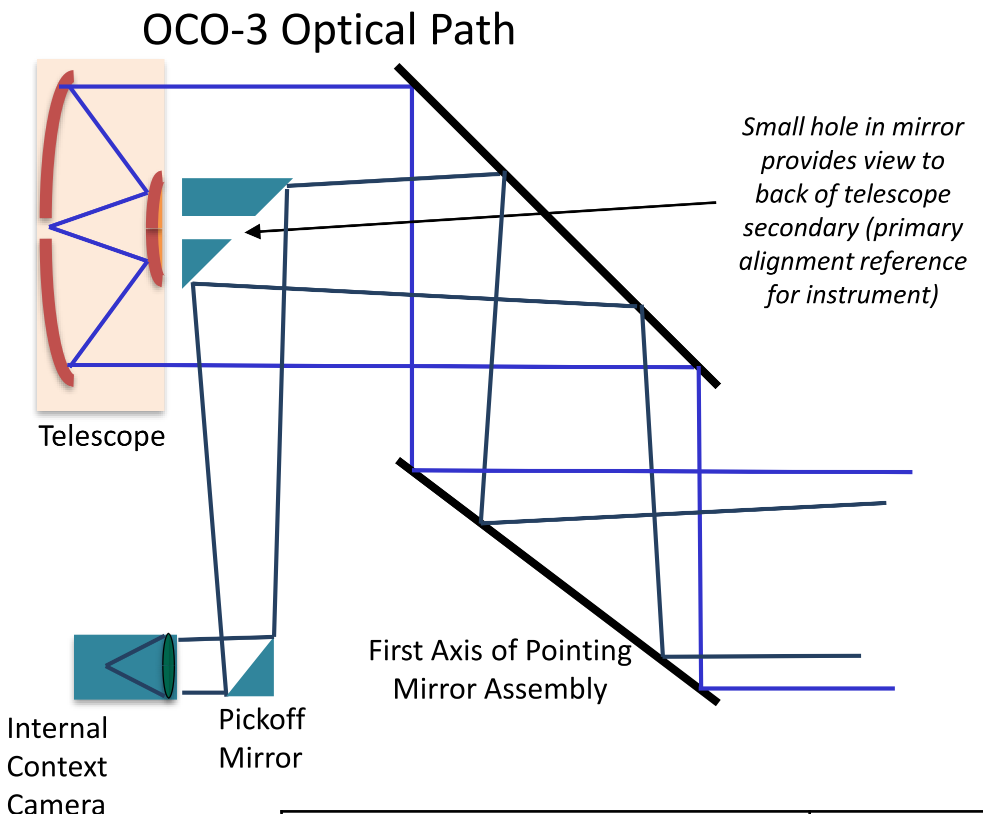
New for OCO-3: Context Cameras to aid in shortening instrument's calibration campaign from months to weeks

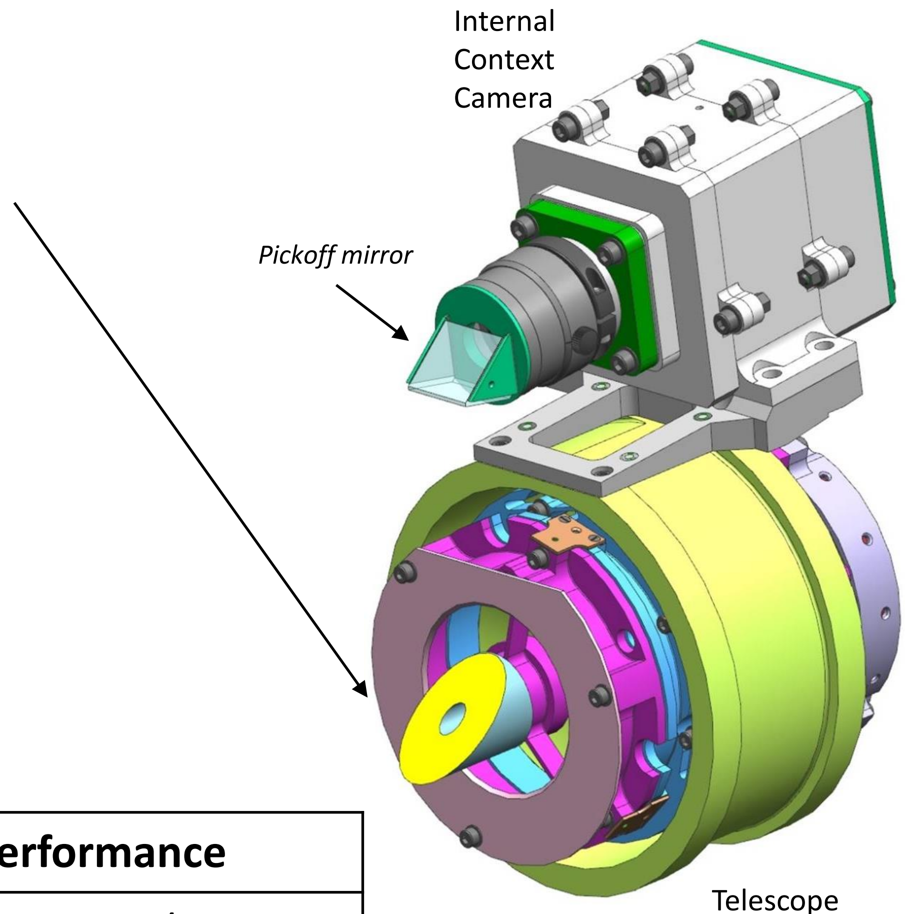
- Internal Context Camera
  - Provides data for alignment and calibration of the instrument's telescope
  - Co-boresighted with instrument's telescope
- External Context Camera
  - Color images covering a wider field of view, providing contextual pointing information of the instrument relative to the Earth's surface
  - Located external to the instrument on Pointing Mirror Assembly

CONTEXT CAMERA SUITE

Overview, Detector and Optics qualification, Electronics architecture, and Mechanical Design

Internal Context Camera (ICC)





ICC Parameter	Performance
Angular Resolution	0.125 mrad/pixel
Field of View (nominal)	5° x 5° 400 x 400 pixels
Detector Pixel Response	Monochrome

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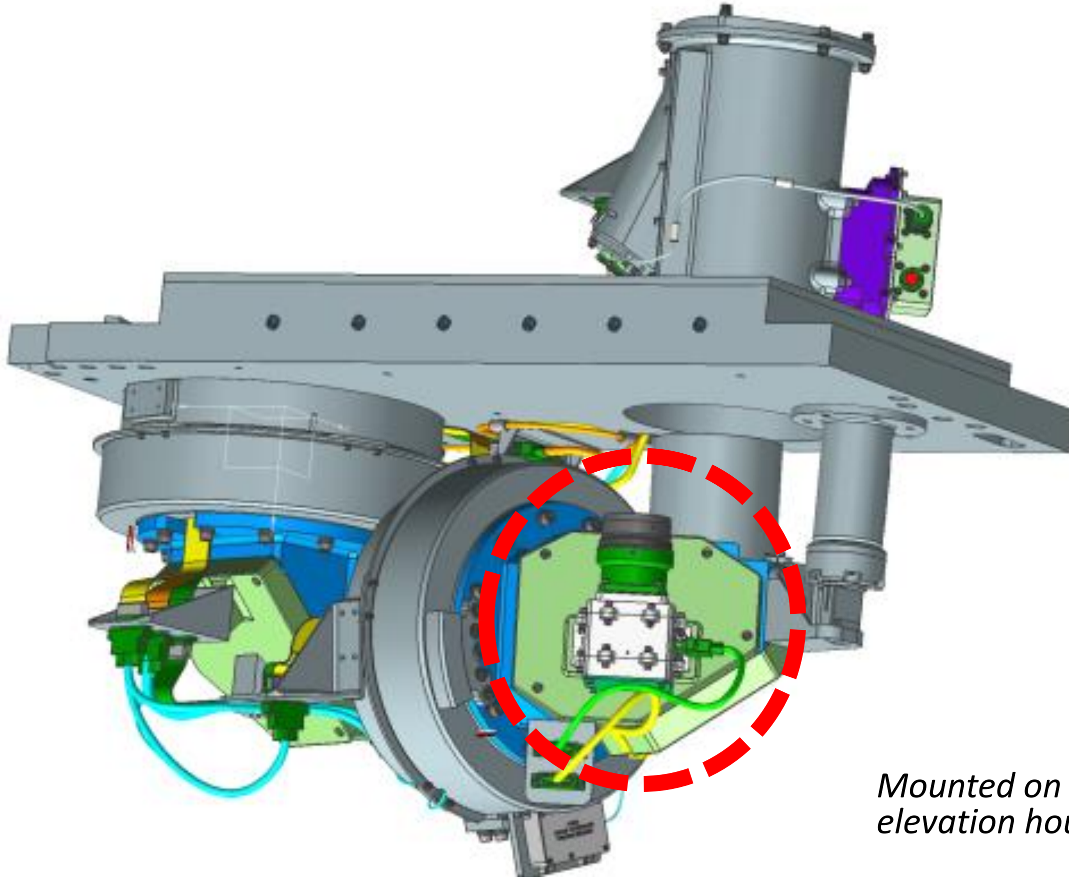
External Context Camera (ECC)



Mounted on PMA elevation housing

ECC Parameter	Performance
Angular Resolution	0.22 mrad/pixel
Field of View (nominal)	32° x 28° 4480 x 3839 pixels
Detector Pixel Response	Color (2X2 Bayer RGB)

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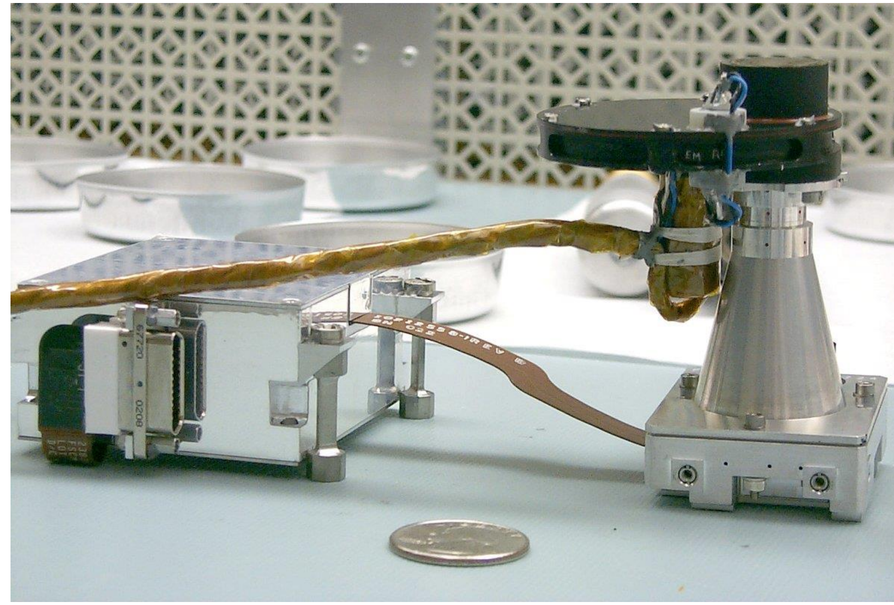
Why not fly a commercial camera?

- Demanding Science/engineering performance requirements
  - High resolution, large format detectors
  - Sensitivity/SNR/Wavelength Cutoff Requirements
  - Tailored Image processing
- Environmental screening (mission assurance)
  - Radiation, wide-temperature operation, assembly techniques
  - Parts screening, derating, performance across temperature



MER Pancam (above) with as-flown electronics, 8-position filter wheel, with 16° x 16° FOV optics **2002/9**

MER Navcam with 45° x 45° optics **2002/7**

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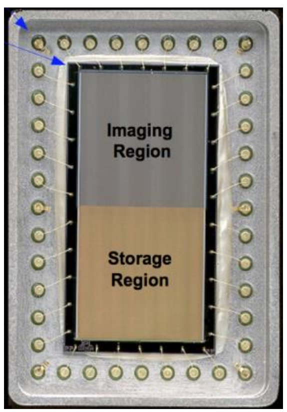
Present and future detectors on JPL/NASA Planetary Cameras

Relative scales preserved

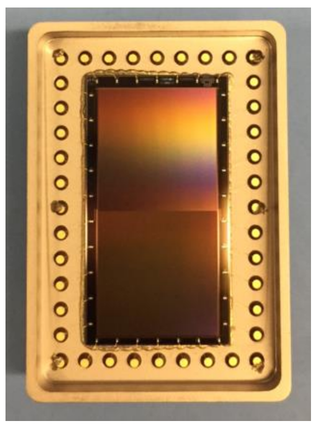
CUSTOM

Custom JPL designed and
fabricated detector
1k x 1k mono CCD



MER, MSL
(Engineering cameras)
2003-2012

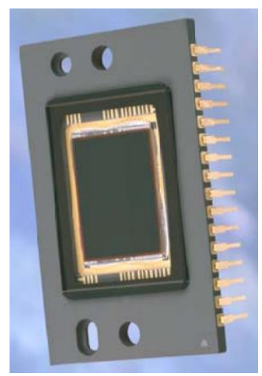
Custom JPL designed and
fabricated detector
1k x 1k CCD, Bayer CFA



Insight IDC/ICC
(2018)

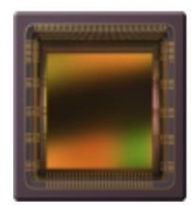
COTS

Kodak TrueSense/ON
Semi KAI-2020
1640x1214
RGB CCD



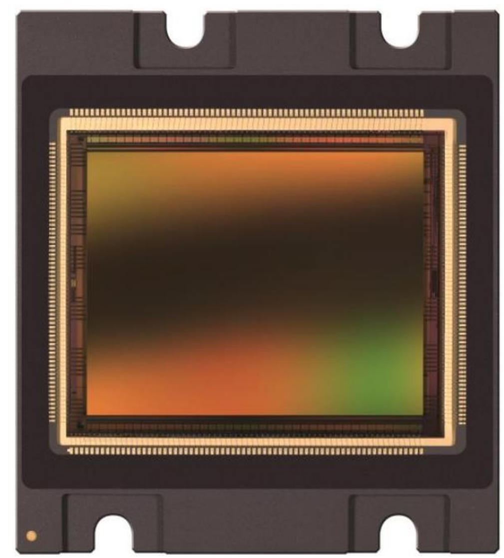
Curiosity MastCam
(2012), M2020
Mastcam-Z
(2020)

CMOSIS
CMV4000
2048x2048
RGB CMOS



M2020
SuperCam RMI
(2020)

CMOSIS CMV20000
5120x3840
RGB/Monochrome CMOS



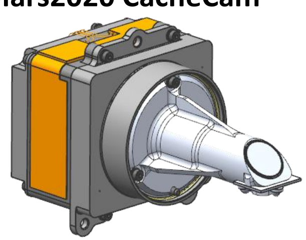
M2020 Engineering cameras
(2020)

Mars2020 Enhanced Engineering Cameras (EECAM)

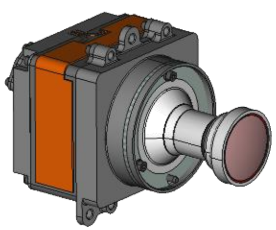
- Successor to MER/MSL Engineering Cameras
- Mission-critical imaging system (Class B hardware)
- Extensive hardware screening and qualification program
- To lower schedule risk, Mars2020 chose to baseline a COTS focal plane array (screened at JPL)
  - Departure from historical Class B imaging system developments
  - Characterization over environments
  - Radiation testing

Key: Significant NRE in the development of EECAM can be infused for OCO-3 Context Cameras

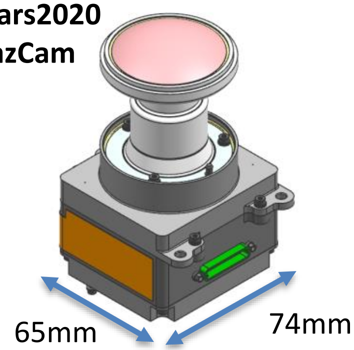
Mars2020 CacheCam



Mars2020 NavCam



Mars2020 HazCam



Mars2020 EECAM Camera Specifications

Sensor Capabilities	
Type	20M Pixel CMOS Image Sensor
Array Size	5120 x 3840
Pixel Size and Pitch	6.4um^2 on 6.4um Pitch
Full well charge	15ke$^-$
Pixel Dark Noise	8e$^-$ RMS
Windowing	Yes
Shutter	Global
Color	Bayer RGB Color
Pixel Quantization	12bit
Electrical Interface	
Commanding & Data	LVDS
Protocol	MER/MSL/Mars2020 NVMCAM
Power Input	+5.5V (+/- 0.4V)
Power	< 3 W
Memory	1Gbit SDRAM
FPGA	MicroSemi Rad-Tolerant ProASIC3
Camera Specifications	
Mass (CBE, no optics)	< 425g
Volume (CBE, no optics)	65 mm x 75 mm x 55 mm
Operating Temperature Range	-55C to +50C
Survival Temperature Range	-135C to +70C
Optics Configurations	
Navigation Camera	95°X 71°(H x V), f/12, iFOV ≤ 0.32 mrad/pix
Hazard Camera	134°X 110°(H x V), f/12, iFOV ≤ 0.46 mrad/pix
Sample Caching System Camera	0.49 magnification, 130mm stop to plane-of-focus, +/- 5mm Depth of Field

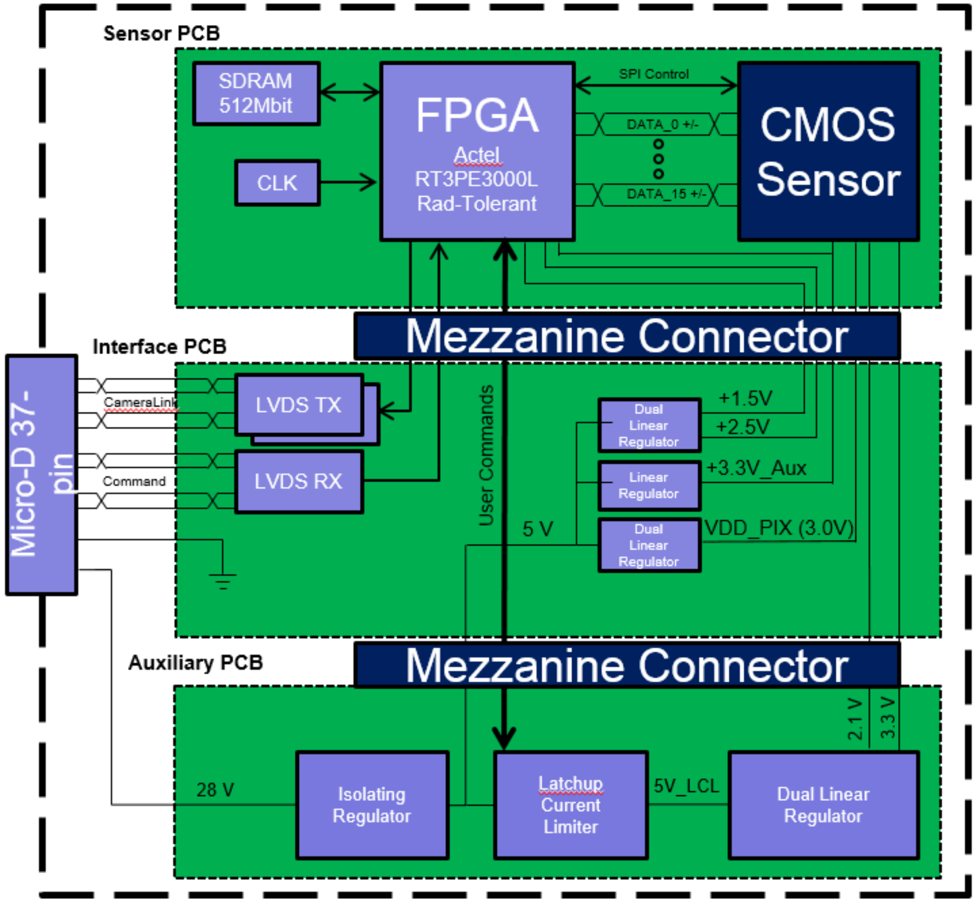
Leveraging JPL flagship hardware developments

Goal: Tailor Mars2020 Enhanced Engineering Camera (EECAM) design to meet OCO-3 mission requirements to reduce cost, schedule, and risk

- Minimal NRE to adapt design (electrical, mechanical)
- Leverage ongoing Mars2020 CMV2000 detector qualification program
- Procure and qualify COTS optics

Electronics Architecture

- Reprogrammable, flash-based FPGA (MicroSemi RT3PE-3000L)
- Physical form-factor/dimensions changes from EECAM without significant modification to design
- Added power conversion from +28V DC ipnut
- Implement OCO-3 camera data protocol over LVDS physical interface with FPGA firmware modification
- Leverage EECAM CMV20000 sensor and data-path interface/firmware



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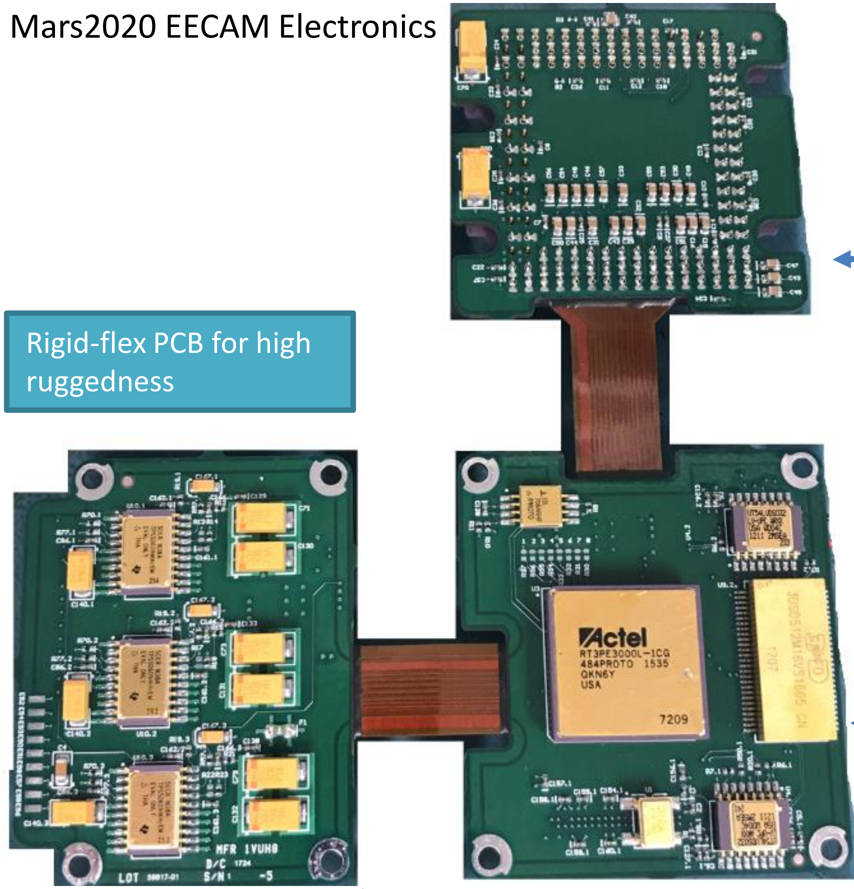
OCO-3 Electronics Implementation

Mars2020 EECAM Electronics



Rigid-flex PCB for high ruggedness

OCO-3 Camera Electronics

Sensor Board

Unit Cost

High Low

Ruggedness

Interface Board

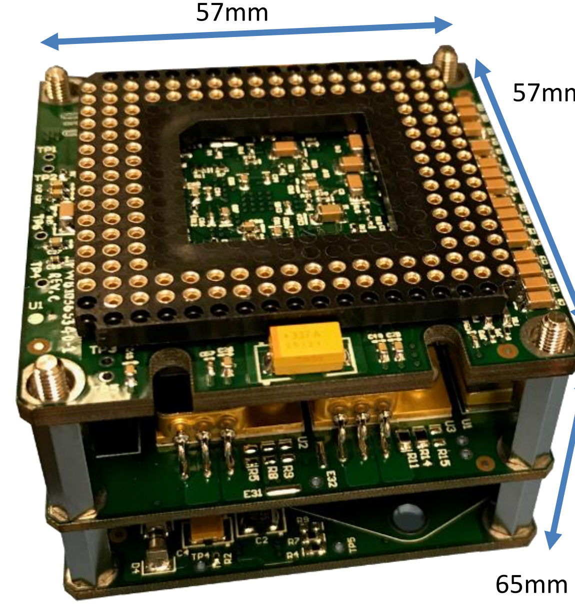
Power Board

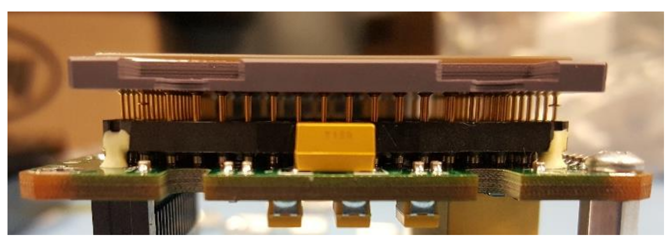
Discrete boards with plastic connector for modular configuration

Context Camera Electronics

Sensor Board	Interface Board	Power Board
Bottom Side	Bottom Side	Bottom Side
		
		
Top Side (no detector)	Top Side	Top Side

Context Camera Integrated Camera Electronics Stack (no detector)





Side view of Sensor board, showing surface-mount BGA socket with detector

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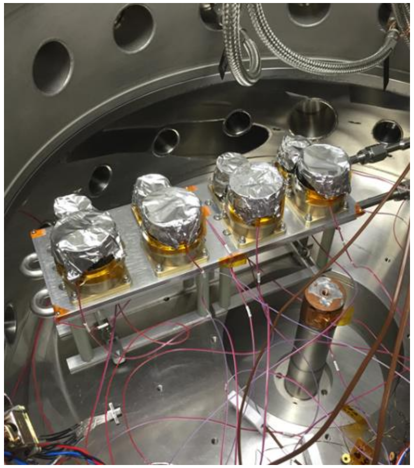
COTS Optics and Qualification

Lens Description

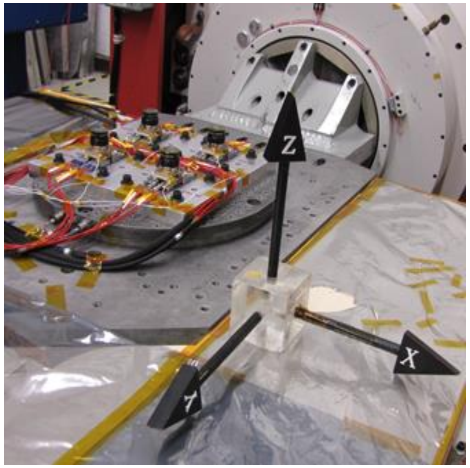
	Internal Context Camera (ICC) lens	External Context Camera (ECC) lens
EFL	29.3 mm	51.2 mm
F# (COTS/OCO-3)	2.0 / 5.0	2.2 / 5.0
Interface	C-mount	V-mount
Image circle	22 mm	43.2 mm
Focus set to	Infinity	Infinity

Temperature Test Levels

Allowable Flight Temperature	Temperature (° C)
Min.	-40
Max.	+70



Lenses in TVAC Qualification Testing



Lenses in Vibration Testing

Vibration Test Levels

Frequency, Hz	Qual/Protoflight Level
20	0.032 g^2/Hz
20 – 50	+6 dB/octave
50 - 300	0.2 g^2/Hz
300 – 2000	-6.0 dB/octave
2000	0.0046 g^2/Hz
Overall	**10.2 grms**

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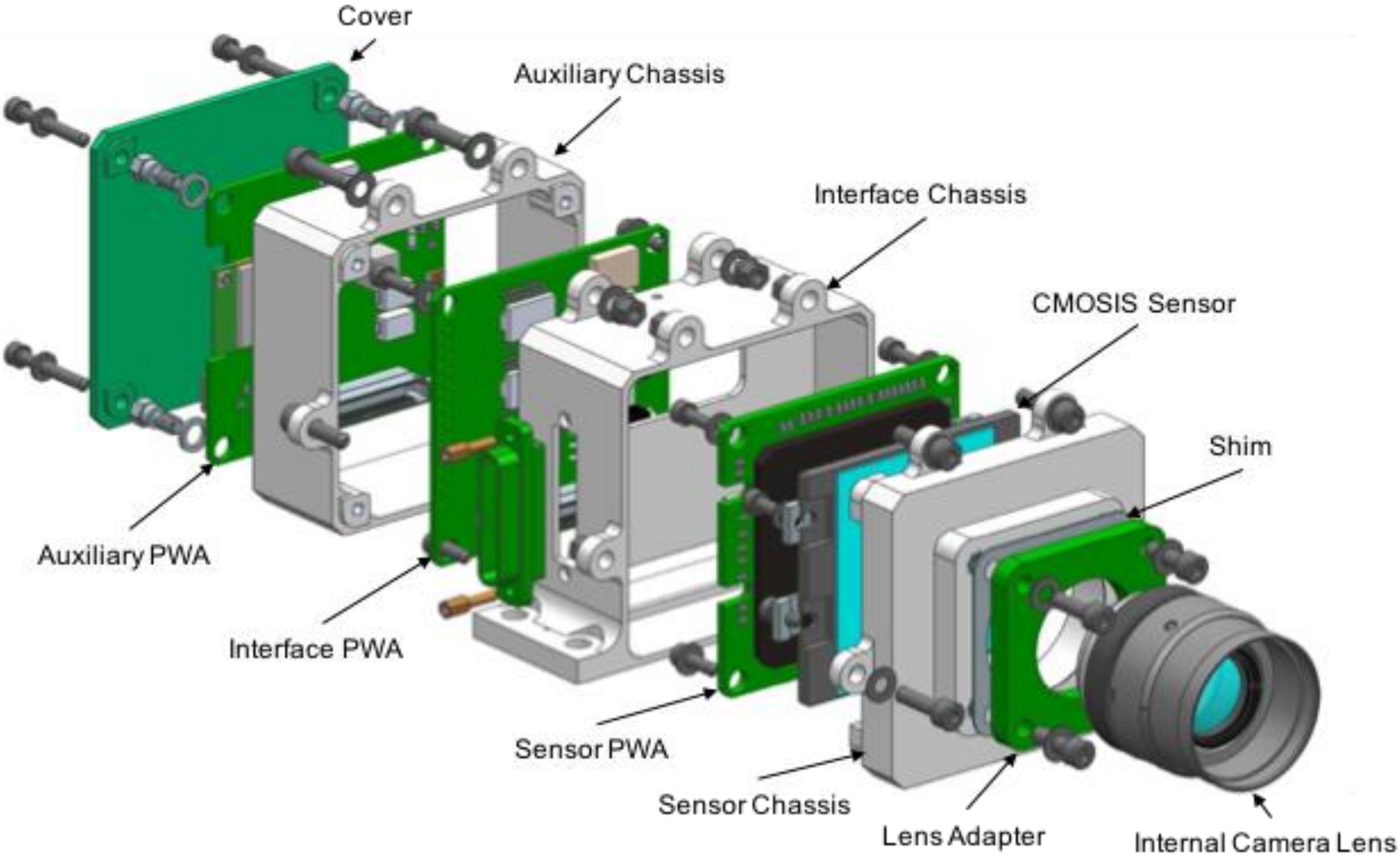
Exploded Camera Assembly



TEST RESULTS

Optical and Environmental Testing

Test Program

Context Camera Suite Capabilities

Imaging Array Size	4480 x 3839 pixels
Pixel Size	6.4µm^2
Pixel Full Well	13k e-
Pixel Bit Depth	12 bits
Shutter	Global
ICC Optics	32° x 28° (H x V), f/5, iFOV < 0.125mrad/pixel
ECC Optics	56° x 48° (H x V), f/5, iFOV < 0.22mrad/pixel
Power	< 5W @ +28V input
Mass	ICC: 460g, ECC: 633g
Volume	ICC: 61mm x 63mm x 120mm ECC: 61mm x 63mm x 155mm

Context Camera Suite Performance vs. Requirements

Parameter	Requirement	Capability
ICC FOV	$\geq$ 4°	40.3° by design, limited by telescope aperture
ICC iFOV	$\leq$ 0.22 mrad	0.22 mrad/pixel
ECC FOV	$\geq$ 25°	28.2°
ECC iFOV	$\leq$ 0.5 mrad/pixel	0.125 mrad/pixel
Minimum SNR	> 100:1	$\leq$ 95:1* * Performance accepted by project, limited by maximum achievable full-well of detector
Maximum Frame Rate	> 0.3 fps.	$\leq$ 3.7 fps (ICC) $\leq$ 0.63 fps (ECC)
Date Rate	< 3 Mbps	1.77 Mbps

- Functional testing
  - Electrical Interface, image acquisition, framerate
- Optical integration
  - Focus, Field of View, and Angular sampling
- Detector calibration
  - Linearity, Quantum efficiency, signal-to-noise, dark current, pixel response non-uniformity
- Environmental Testing (at next level of assembly)
  - Thermal Vacuum cycling
  - Vibration testing
  - Pyroshock testing

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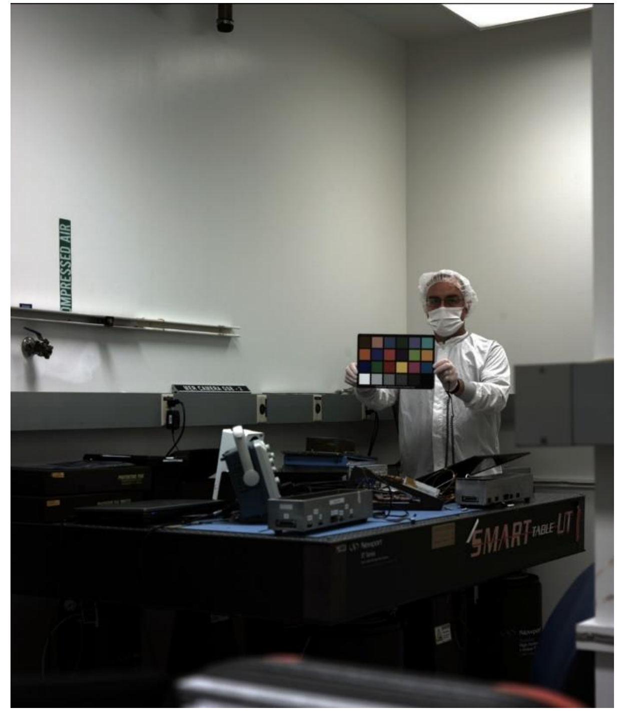
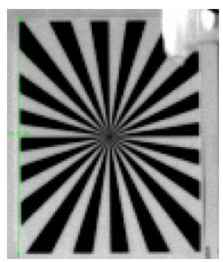
Optical testing

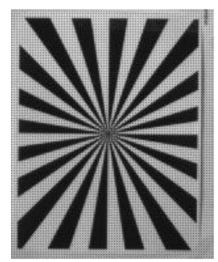


Internal Context Camera

$iFOV_{ICC} = 0.22\ mrad/pixel$

$FOV_{ICC} = 986\ x\ 845\ mrad = 56.5° \boldsymbol{x}\ 48.4°$





External Context Camera

$iFOV_{ECC} = 0.125\ mrad/pixel$

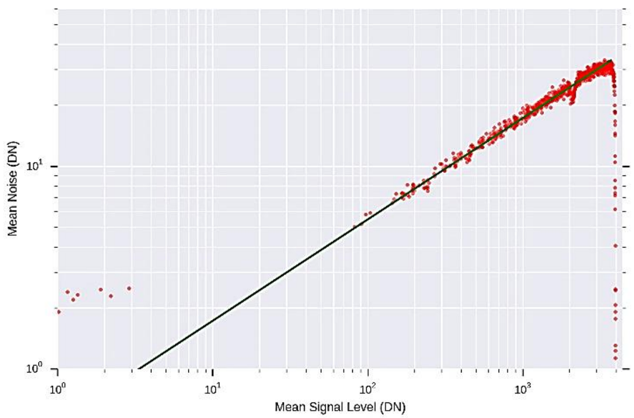
$FOV_{ECC} = 561\ x\ 492\ mrad = 32.1° \boldsymbol{x}\ 28.2°$

$$iFOV_{radians} = \frac{\arctan\left(\frac{2 * f}{d}\right)}{\#\ of\ pixels}$$

$$FOV_{rad} = (Pixels_{Horizontal}\ x\ Pixels_{Vertical}) * iFOV$$

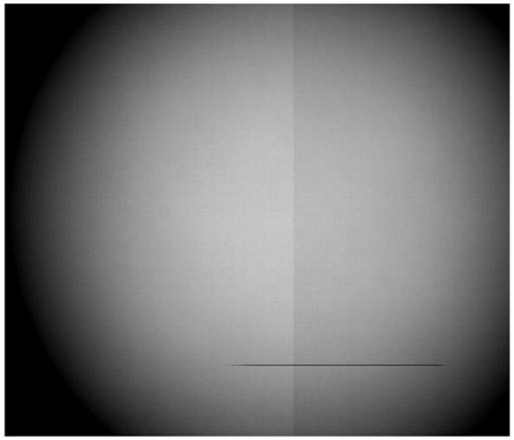
Detector Calibration

ICC Photon Transfer Curve and Detector Settings

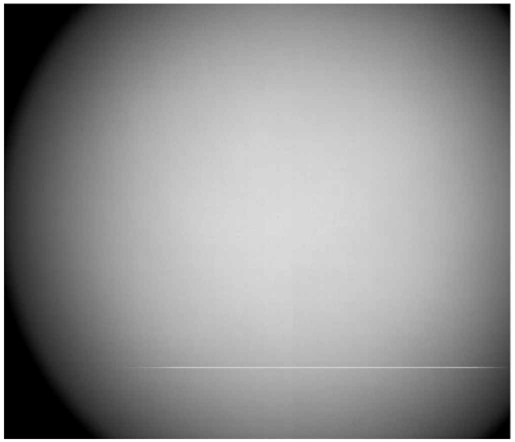


Camera	ADC Gain	PGA Gain	Conversion Gain (e⁻/DN)	Full Well (e⁻)	Full well (DN)	ADC Saturated (4095DN)
ICC	57	1x	3.4	13000	3800	Close
ECC	57	1x	3.5	12800	3650	No

Pixel response non-uniformity (PRNU) correction

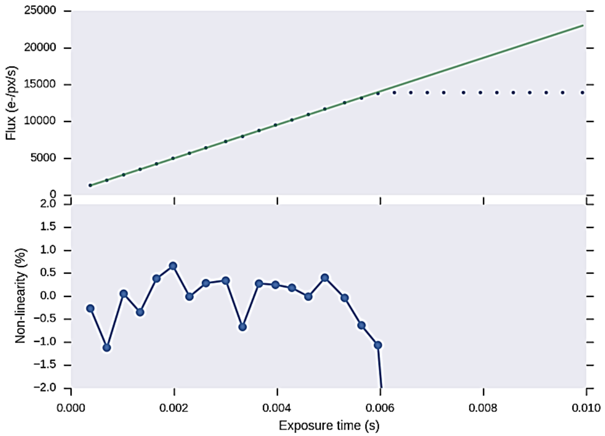


ICC average flat fields before correction

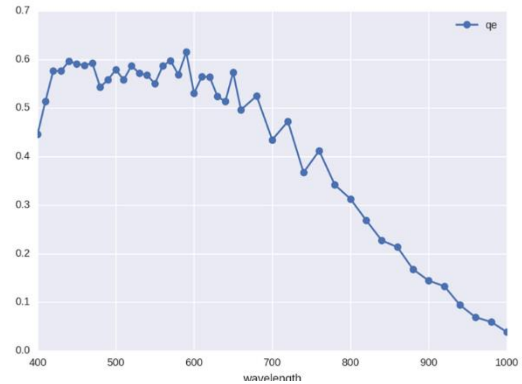


ICC average flat fields after correction

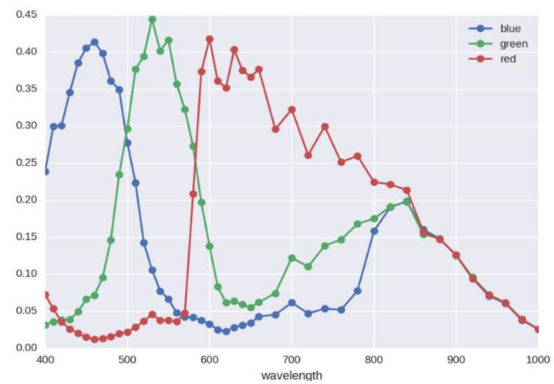
Detector Linearity Plot



Quantum Efficiency



ICC (monochrome)



ECC (RGB color)

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Environmental Testing

- Performed at next level of integration
  - ICC: Integrated with telescope entrance optics
  - ECC: Integrated with Pointing Mirror Assembly

Context Camera TVAC Levels

Allowable Flight Temperature	Temperature (° C)
Min.	-20
Max.	+60

Context Camera Test Vibration Levels

Test Article	Frequency (Hz)	Flight Acceptance Levels	Qualification/ Protoflight Levels
Internal/External Context Cameras, Entrance Optics	20	0.008 g2/Hz	0.016 g2/Hz
	20-50	+ 6 dB/octave	+ 6 dB/octave
	50-300	0.05 g2/Hz	0.10 g2/Hz
	300-2000	- 6 dB/octave	- 6 dB/octave
	2000	0.0011 g2/Hz	0.0023 g2/Hz
	Overall	5.1 grms	7.2 grms

External Context Camera Pyroshock Levels

Test Article	Frequency (Hz)	Maximum Shock input to payload (g-peak SRS)	Maximum Shock input to payload +3 dB (g-peak SRS)
External Context Cameras, PMA	100	52	73
	1300	3000	4200
	10,000	3000	4200

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Future Uses

- Visual odometry during Entry, Descent, and Landing (EDL) for planetary landers and rovers
- Stereo Motion tracking and centroiding for space rendezvous

Summary

- Two context cameras, adapted from Mars2020 Engineering Cameras, were designed, built, and tested at NASA JPL

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